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13. ABSTRACT (Maximum 200 words)

Our work has focused on two principal aspects: (a) developing a rigorous modal transmission-line (MTL) approach for modeling quantum-well infrared photodetectors (QWIPs) and other optoelectronic devices. and (b) applying this approach to evaluate the performance of actual QWIPs. The geometry of the QWIPs may include any number of different dielectric and metallic layers, which may generally be periodic with arbitrary profiles, The theoretical part (a) was carried out for both two-dimensional lamellar and three-dimensional grid geometries. In the applied part (b), we have obtained numerical results for QWIPs under experimental study by scientists at the Army Research Laboratory (ARL) and Princeton University, with whom we collaborated on a continuous basis. Our analytical results show very good agreement with the experimental data, thus establishing that our MTL modeling is both powerful and accurate. Using this approach, we have also derived design criteria for a wide variety of QWIPs, which were subsequently fabricated with specifications that conformed to our design guidelines. In addition, we have developed design procedures for new QWIPs for focal plane arrays, as well as novel QWIP geometries to be used as two-color detectors, or as spectrometers over a wide frequency range. These newer devices are presently in the fabrication stage at ARL.

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Foreword

The following is our final report on the project entitled "Electromagnetic modeling of quantum-well infrared photodetectors," which started on 20 April, 1999, and was completed (after being extended) on August 19, 2003.

The principal aim of this research work was to develop analytical models of periodic configurations that occur mostly in quantum-well infrared photodetectors (QWIPs), as well as in other optoelectronic devices. To strengthen this theoretical study, a close collaboration was maintained with the Dr. K.-K. Choi's group at the Electro-Optics and Photonics Division, Army Research Laboratory, Adelphi, MD, and with Prof. D. C. Tsui's group at the Department of Electrical Engineering, Princeton University, Princeton, NJ. This has enabled us to apply our electromagnetic modeling techniques to a variety of QWIP configurations under active experimental investigation by those two groups. We have thus arrived at interesting and useful explanations of their measurements and have provided guidance in designing their experimental efforts.

The major achievement of our study was the development of a rigorous modal approach for the analysis and design of multilayered QWIP configurations that incorporate arbitrarily shaped periodic contours, and contain materials consisting of lossy dielectric media and metallic conductors. This modal approach provides physical insight into the detection process, on the one hand, and readily performs an accurate evaluation of the photocurrent characteristics, on the other hand. Furthermore, our approach employs transmission-line techniques that serve as a very powerful tool in the engineering design of QWIP structures having specialized and/or desirable characteristics, such as high efficiency, two-color detection capability, narrow or wide bandwidths, etc. As described herein the theoretical basis of our rigorous analytical approach, its associated transmission-line and computational techniques, and its application to a wide variety of QWIP configurations have been published in the professional literature and reported at both general and specialized professional meetings.

Statement of the problem studied

Quantum well infrared photodetectors (QWIPs) generally consist of a quantum well (QW) region inserted between conducting layers that serve as electrodes. Additional layers are also present due to specific device requirements or fabrication purposes. The material forming a QWIP are GaAs and $Al_xGa_{1-x}As$, but other materials (such as MgF_2, epoxy, gold or other conductors) are also part of the complete QWIP device. Because only the incident electric component normal to the QW layers generates photocurrent, it is necessary to incorporate a mechanism that deflects the field into that desired direction. This can be achieved by a grating configuration, which can be above or below the QW layer.[1-3] Alternatively, the QW layer can itself be formed into a periodic structure, thus serving as the required grating.[4, 5] Because the latter situation is easier to fabricate and exhibits a variety of other advantages, we shall assume that this is the case for illustration purposes.

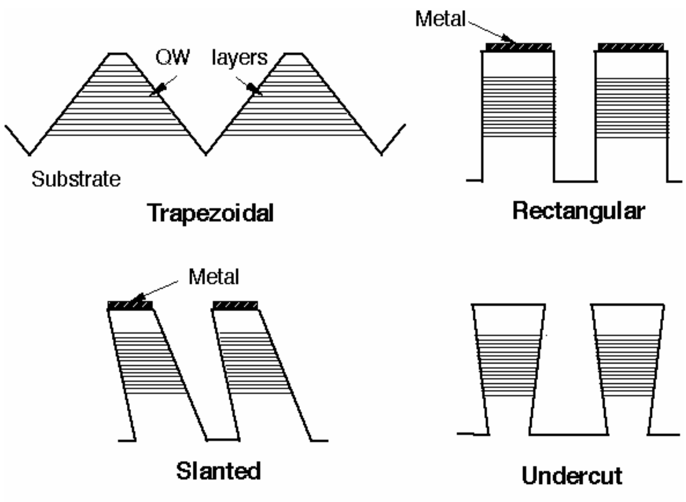


Fig. 1: Typical lamellar QWIPs

Several QWIP configurations are shown in Fig. 1, where the periodic portions

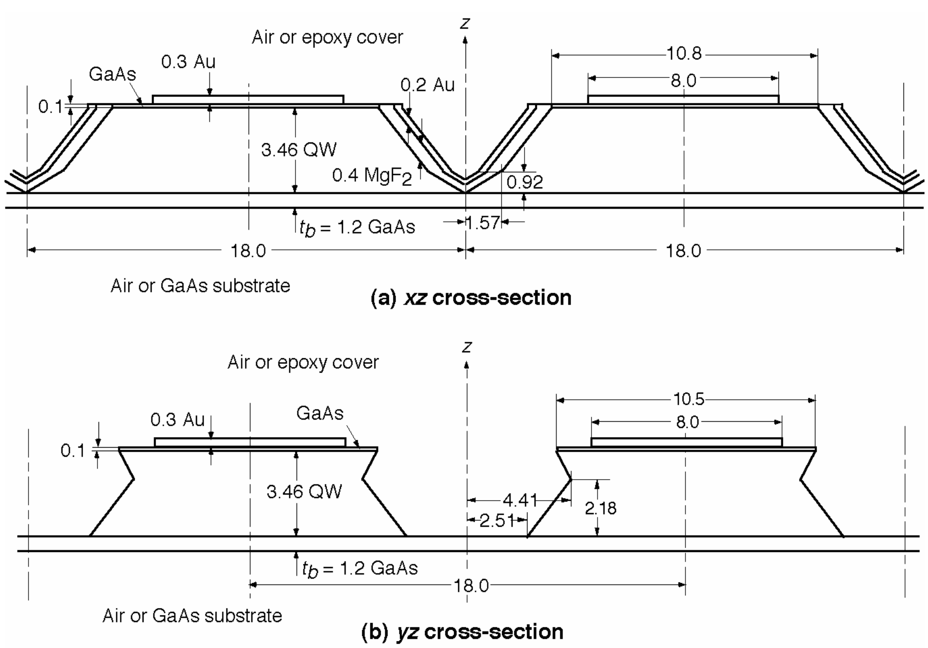


Fig. 2: Grid QWIP with gold and MgF2 layers

consist of rectangular or trapezoidal cells, which may be symmetric or slanted, either in-

tentionally or due to the fabrication (etching) process. Because of their basic lamellar form, these QWIPs can be treated by a simple two-dimensional analysis. A more complex QWIP structure is shown in Fig. 2, where all dimensions are in μm. A large number of layers and different materials are present and the materials include gold (Au), whose electromagnetic behavior is very much different from that of the dielectric materials occupying most of the QWIP configuration. Because the QWIP in Fig. 2 is periodic along both horizontal directions, it forms a grid having trapezoidal *xz* and hourglass *yz* cross-sections, which involves a three-dimensional geometry. Obviously, finding the electromagnetic fields due to energy incident on such a configuration poses a formidable boundary-value problem if an accurate electromagnetic field solution is required.

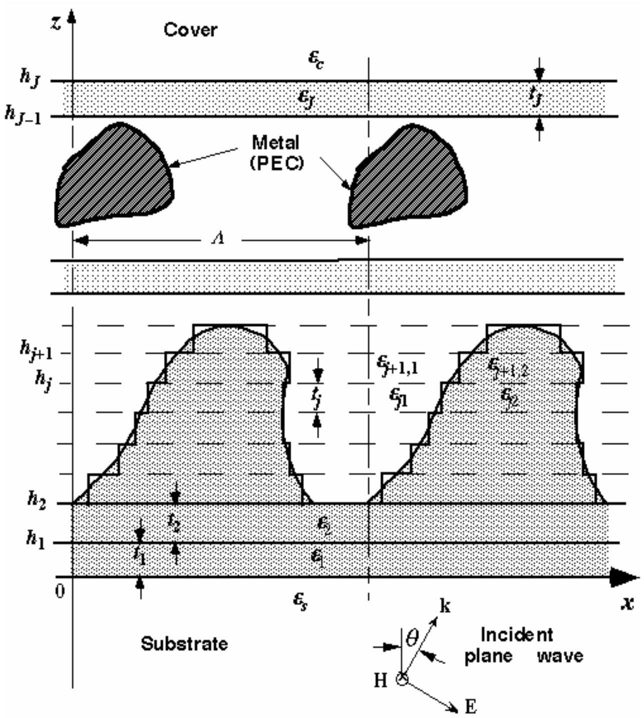


Fig. 3: General geometry of QWIP configurations

To accommodate the large variety of structures illustrated in Figs. 1 and 2, we have explored[6, 7] the general situation described in Fig. 3, where an electromagnetic field is incident from below into the substrate of a multilayered stack containing periodic elements having arbitrary shapes and materials. The configuration in Fig. 3 allows for arbitrarily shaped periodic regions, and the materials can generally be lossy biaxial dielectrics and/or metallic media, including perfect electric conductors (PECs). As shown here, the geometries in Figs. 1 and 3 are two-dimensional (2D) and refer to lamellar QWIP configurations. However, we have also extended our results to three-dimensional (3D) grid configurations,[8] such as that shown in Fig. 2, by allowing for periodic variations along the *y* coordinate in Fig. 3.

In all cases, we have developed rigorous analytical solutions that, as described in the next Section, yield the electromagnetic fields at any point in the QWIP structure. By obtaining these fields, it is then possible to derive the power absorption in the QW layers and thus evaluate the photocurrent. This, in turn, determines the quantum efficiency. Other characteristics of the C-QWIP device can similarly be obtained from the field quantities. We have applied these analytical tools to construct computational programs and obtained results for the experimental QWIPs developed by the ARL and Princeton University groups. As described further below, the agreement between our theoretical modeling and their experimental data was very high.

Summary of the most important results

The results achieved by our work fall into two principal categories. The first one is the development of a rigorous analytical solution for the electromagnetic problem posed by the general situation shown in Fig. 3. The second category is the application of this solution to a wide variety of actual QWIP structures. Of these, most have already been (or are expected to be) fabricated and tested by the ARL and Princeton University groups. In this context, we have developed criteria for designing QWIP configurations having novel functions or desirable improved characteristics. Based on these design considerations, new QWIP configurations are either being fabricated for immediate testing, or under consideration for future applications, as further described below.

A. Rigorous electromagnetic modeling

The requisite analytical models for the general periodic structure in Fig. 3 were developed sequentially as follows:

(i) It was first assumed that the materials were dielectrics having complex refractive index, which included metals but not perfect electric conductors (PECs). Periodic regions having arbitrary profiles were subdivided into sufficiently many $j = 1, 2, \dots J$ thin layers, each of which was then approximated by a step-wise periodic region of height t_j and uniform periodic regions having dielectric constants ε_j, ε_{j+1}, ε_{j+2}, … , as shown in the periodic layer of Fig. 3. By using a rigorous modal approach, the scattering of a plane wave by such a structure can then be described in terms of an equivalent transmission-line network.[6] Specifically, for a relatively simple situation having a periodic layer embedded in regions having homogeneous dielectric media, such a network is shown in Fig. 4.

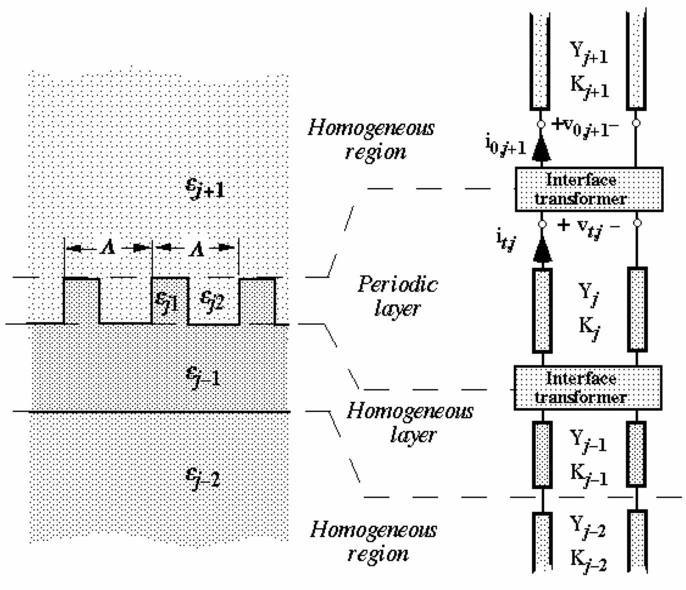


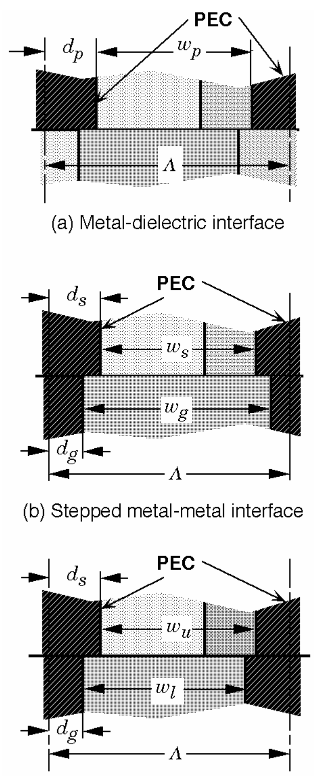
Fig. 4 - Typical portion of a grating geometry and its equivalent network representation

The transmission lines shown here are given by matrix forms of characteristic admittances $\mathbf{Y}_j$ and propagation factors $\mathbf{K}_j$, whose individual terms represent the various diffracted orders supported by the periodic region. All of these lines are connected in tandem, except that interface transformers are needed at the junctions with the periodic layer. By using units such as that shown in Fig. 4, it is possible to construct the solution to any arbitrary geometry as in Fig. 3.

At this stage of our project, the analysis was restricted to 2D geometries of the lamellar form, but the dielectric media could be uniaxial, so that QW regions were easily accommodated. For these cases, the interface transformers shown in Fig. 4 had

simple matrix relations, which were determined by requiring that the fields of each diffracted order were continuous at the interface.

(ii) The above phase provided a convenient modeling capability for devices containing dielectric media, as well as metals in the form of thin horizontal plates. However, for components consisting of highly conducting metals (e.g., gold or silver) having thicker dimensions, the corresponding computational program converged slowly. To avoid this aspect, the second phase of our study[7] extended the analysis to geometries that included PECs, which were found to provide excellent numerical results for situations involving such highly conducting media. The presence of such PECs does not change the transmission-line aspect depicted in Fig. 4, but it strongly affects the analytical expressions for the interface transformers.



(a) Metal-dielectric interface

(b) Stepped metal-metal interface

(c) Offset metal-metal interface

Fig. 5: Typical metallic interfaces

Some of the geometries involving PEC materials are shown in Fig. 5, for which the interface transformations have been analytically derived and applied to specific practical situations. In conjunction with the transmission-line networks illustrated in Fig. 4, these transformations served as templates for computational programs that provided accurate results for the operation of actual lamellar devices whose performance had been experimentally determined. Because the agreement between the experimental data and the theoretical model was very good to excellent,[9, 10] our modal approach can readily serve as a powerful tool for both analysis and design purposes.[11-13]

(iii) The preceding discussion has dealt primarily with 2D lamellar configurations. For the more general situation having periodic variations with respect to both x and y coordinates, e.g., for QWIPs of the grid type in a focal plane array, a 3D geometry is needed. We have therefore extended[8] our 2D modal transmission-line approach to 3D and have successfully examined several practical situations. In particular, the complex geometry shown in Fig. 2 was examined and design criteria were established for particular focal-plane arrays.[13] Such arrays have been fabricated and preliminary data have shown good agreement with our theoretical results, but the work is still ongoing and a more thorough comparison between our modeling approach and the actual experimental data remains to be obtained at a later date.

B. Evaluation and design of specific QWIP configurations

The rigorous modeling approach described above was applied to evaluate the performance of experimental QWIPs and to design new configurations, as described below.

(i) The performance of lamellar QWIPs having a slanted trapezoidal profile (as shown in Fig. 1) was evaluated and the theoretical results[6] showed excellent agreement with the experimental data.[9] This agreement was especially significant since the QWIP

performance was analytically predicted without any adjustable parameters, on the one hand, and its geometry involved an asymmetric grating, on the other hand.

(ii) Design criteria were established for lamellar QWIPs having rectangular gratings in a grid configuration.[10] The top of the rectangular corrugations were covered by a thin gold layer. As in item (i) above, the agreement between the analytical predictions and the experimental results was excellent. Most importantly, we have thus shown that the metal top dimensions play a critical role in maximizing the photocurrent. Specifically, that current peaks if the width of the metal layer is equal to an odd number of half wavelengths in the material. This occurs because the induced current in the metal acts as an electric dipole whose behavior serves as an effective design criterion to optimize performance at desirable wavelengths.

(iii) Based on the results obtained in item (ii) above, we have established the groundwork for constructing a spectrometer using QWIP elements.[11, 12] This device consists of channels containing those elements in a grid pattern. The dimensions of the QWIPs in the channels are tailored to provide response peaks at different wavelengths. Design criteria were developed for a spectrometer containing up to 10 such channels and operating in the range 7.5 - 12.0 μm, as well as in a broader 6.0 - 15.0 μm range. Preliminary experimental results support this concept and its design feasibility.

(iv) A broad variety of QWIPs having triangular or trapezoidal grating profiles were examined[6, 12, 13] under different conditions, e.g., with or without metal tops, with air or epoxy covers, placed over thick or thinned substrates, etc. The results have shown that the placement and dimensions of the metal tops may enhance performance in certain cases, but the presence of epoxy cover and/or additional insulating layers (usually, MgF_2 material) could degrade performance. All of these considerations have provided a plethora of design considerations, most of which have been verified experimentally.

(v) The complex grid structure shown in Fig. 2 for constructing a 1024 x 1024 focal plane array was analyzed and numerical results have shown that it can provide an effective performance over a broad 7.5 - 11.5 μm wavelength range.[13] This desirable performance is satisfactorily maintained if the structure uses an epoxy cover and has a thin substrate. Hence such a focal plane array can serve as the active component in an infrared imaging camera.

(vi) Using 3D analysis, we have evaluated the performance of grid QWIPs in which each lattice contains a post incorporating QW layers.[8] The posts may have circular, square or triangular cross-sections, thus leading to different detection efficiencies, which are subject to the symmetry posed by the relevant cross-sections. The results show that the circular posts provide optimum performance and their high symmetry renders them least susceptible to variation in fabrication.

Publications

A. Papers published in peer-reviewed journals

L. Yan, M. Jiang, T. Tamir and K.-K. Choi, "Electromagnetic modeling of quantum well photodetectors containing diffractive elements," IEEE J. Quantum Electron. **35**, 1870-1877; December 1999.

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C.-H. Lin, K. M. Leung and T. Tamir, "Modal transmission-line theory of three dimensional periodic structures with arbitrary lattice configurations," J. Opt. Soc. Am. A **19**, 2005-2017; Oct. 2002.

K.-K. Choi, C. H. Lin, K. M. Leung, T. Tamir, J. Mao, D. C. Tsui and M. Jhabvala, "Broadband and narrow band light coupling for QWIPs," Infrared Phys. Technol. **44**, pp. 309-324; Oct.-Dec. 2003.

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K. M. Leung, C.-H. Lin, T. Tamir and K.-K. Choi, "Analysis of metal grating diffraction by models with perfect electric conductors," 2003 Annual OSA Meeting, Tucson, AZ; October 2003.

D. Manuscript submitted but not yet published

K.-K. Choi, K. M. Leung, T. Tamir and C. Monroy, "Light coupling characteristics of corrugated quantum well infrared photodetectors," IEEE J. Quant. Electr., acccepted for publication.

List of Participating Scientific Personnel

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B. Research Associates: Mr. Shuzhang Zhang
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C. Post-Doctoral Fellow: Dr. Mingming Jiang

D. Research Fellow: Dr. Chung-Hsiang Lin (completed a Ph.D. degree in Elec trical Engineering while working on this project).

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